Vibro-Electric Transfer Path Analysis of a Solid Body Electric Guitar

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Abstract

Solid Bodied electric guitars typically employ one or more magnetic pickups attached to the guitar body in close proximity to the guitar strings. At low frequencies the amplitude of the vibrating string is typically far greater than vibrations transmitted through the guitar body and it is likely therefore that the output current is largely dominated by the string vibrations with little contribution from the guitar body itself. However, musicians often describe subjective differences between instruments made from different body materials, with mahogany often being cited as sounding 'warm' for example. Described in the presentation is a method that has been used to determine the contribution to the guitar signal from just the guitar body itself so as to estimate at what frequencies the guitar body may make a significant contribution to a guitar's 'tone' if any. The method is similar to the approach used to diagnose structure borne noise problems in vehicles and aircraft known as transfer path analysis. However, instead of determining forces and their contribution to vehicle interior sound pressure, we determine the forces applied to a guitar body through the bridge and nut together with their contributions to the guitar output signal. In this way the contribution of the string and the guitar body can be found independently and compared to the guitars total output signal. Preliminary experimental findings from a vibro-electric transfer path analysis of a Gibson Les Paul type guitar are presented.

Introduction

In recent years there has been significant debate regarding the affect the body and neck material on the sound or 'tone' of a solid body electric guitar. This paper describes a method to quantify the contribution to the output voltage of a solid body electric guitar resulting from forces on the bridge and nut. We refer to this method as 'Vibro-Electric Transfer Path Analysis'. Results are presented that validate the method, and a comparison is made between the contributions in the guitar output voltage due to body-borne vibrations and string-motion as transduced by the electro-magnetic pickups. In the following section the background and theory of the method is set out. This is followed by a description of the experimental setup and a discussion of the results obtained for a solid mahogany body electric guitar from the manufacturer Gordon Smith. Finally conclusions are drawn at the end of the paper together with suggestions for further research.

Theory

Transfer Path Analysis (TPA) [1] is widely used in the automotive industry for rank ordering noise and vibration sources and their associated transfer paths. For example, the approach is used for the analysis of structure borne road or engine noise in vehicles [2]. An alternative to the conventional inverse TPA approach which allows all measurements, FRF (Frequency Response Function) and operational, to be performed in the coupled state is now also widely used [2].

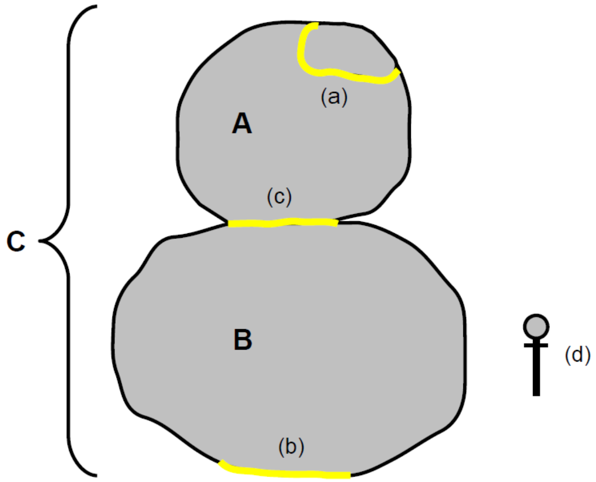

Figure 1 – Illustration of an arbitrary source-receiver system

Shown in Figure 1 is a schematic of a vibration source coupled to a receiver structure. It can be seen that the vibration source (A), defined as having multiple generalised forces at (a) during operation, may in turn apply forces to the receiver structure (B) through the interface (c). The sound pressure(s) at some position(s) (d) will then be a combination of the airborne sound radiated by structure (A) and the structure borne sound radiated by structure (B). The blocked force of a the vibration source (A) can be determined from measurements performed in-situ [3] by solving,

$$\dot{\overline{\mathbf{f}}}_{\mathbf{A,c}} = \left[\frac{\mathbf{Y}_{\mathbf{C,cc}}}{\mathbf{Y}_{\mathbf{C,bc}}}\right]^{+} \left\{\frac{\dot{\mathbf{v}}_{\mathbf{C,c}}}{\dot{\mathbf{v}}_{\mathbf{C,b}}}\right\} \qquad \text{Eq.1}$$

Where $\dot{\overline{\boldsymbol{f}}}_{\boldsymbol{A,c}}$ is the blocked force (blocked condition identified by bar) of the vibration source (A) expressed in terms of the mobility and the operational velocity of the assembly (C). The blocked forces applied at interface (c) are related to the sound pressures at (d) by vibro-acoustic FRFs of the assembly $\mathbf{H}_{\mathbf{C,dc}}$ by,

$$\dot{\mathbf{p}}_{\mathbf{C,d}} = \mathbf{H}_{\mathbf{C,dc}}\dot{\overline{\mathbf{f}}}_{\mathbf{A,c}} \qquad \text{Eq.2}$$

where $\boldsymbol{H}_{\boldsymbol{C},\boldsymbol{dc}}$ would typically be measured at the same time as $\boldsymbol{Y}_{\boldsymbol{C},\boldsymbol{cc}}$ by recording the sound pressure due to a unit force input at the degrees of freedom (c).

If we now consider the assembly C as a solid body electric guitar where the strings nut and bridge are sub-system (A) and the guitar body, neck and electrics are sub-system (B) one can determine the blocked forces at the bridge and nut using equation (1) and if the response at (d) is instead the output voltage of the guitar, **V**, we may instead write,

$$\dot{\mathbf{V}}_{\mathbf{C,d}} = \mathbf{H}_{\mathbf{C,dc}}\dot{\bar{\mathbf{f}}}_{\mathbf{A,c}} \qquad \text{Eq.3}$$

and this in turn allows the contribution of the forces on the guitar body to be related to the output voltage of the guitar. If this voltage is then compared to the actual output voltage of the guitar the relative contributions of string and body can be quantified as a function of frequency. This approach we shall refer to as a “vibro-electric transfer path analysis”.

Measurement Setup

Shown in figure 2 is a photograph of the experimental setup. Two guitars were tested: A Gordon Smith Graduate and a Gibson Les Paul. The results presented in this paper are for the Gordon Smith guitar; both guitars had mahogany bodies which are often described as having a warm sound implying emphasised low frequency content.

Figure 2 – Gordon Smith Electric guitar in the semi anechoic chamber. One of Two guitars tested.

The guitar bridge was instrumented as shown in figure 3. Three accelerometers were used at each of the guitar bridge’s couplings to the body in order to capture translations in the x, y and z planes. Rotations were not taken into account. The nut of the guitar was instrumented similarly but taking into account only the translations perpendicular to the string.

In order to verify the forces measured at the bridge and nut the guitar was instrumented with one additional accelerometer for which a prediction of the vibration acceleration could be made and compared to the actual vibration acceleration measured at the same time. Such a prediction is shown in figure 4 for the low E-string when excited using an E-bow.

Figure 3 – Gordon Smith Electric guitar instrumented with six single axis accelerometers in order to capture three degrees of freedom of coupling of the guitar bridge screws to the guitar body.

It can be seen in figure 4 that the vibrations of the guitar body can be predicted well using the measured blocked forces at the bridge and nut of the guitar. This implies that the blocked forces obtained are reliable and thus can be used to predict the output voltage of the guitar resulting from the body vibrations alone. This in turn can then be compared to the total output voltage of the guitar to determine whether the body vibrations are a significant contributor to the guitar's 'tone'. It should be noted however that this approach only demonstrates the extent to which the guitar body vibrations contribute to the output voltage of the guitar but it does not identify the extent to which the guitar body may influence the vibration of the strings themselves which could also potentially affect the 'tone' or more likely the sustain. This is a subject for further research and is not addressed in this paper.

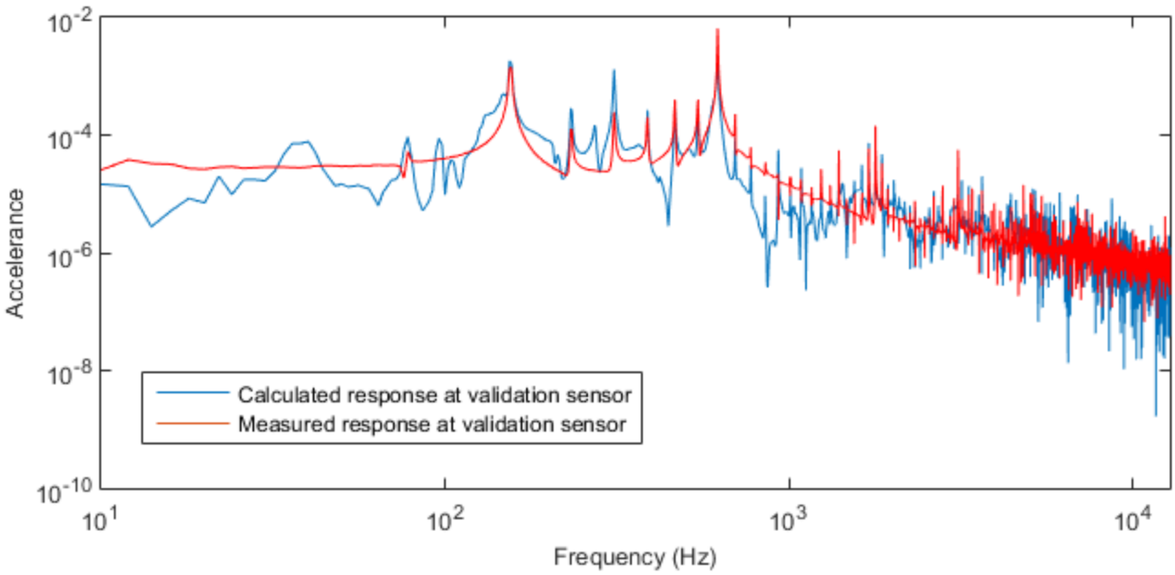

Figure 4 – On board validation: The vibration measured on the guitar body is compared to that which is predicted from the measured blocked forces at the bridge and nut.

Contribution Analysis

Shown in figure 5 is the total output voltage of the guitar when the open E-string is excited with an E-bow (red line). This is compared to the output voltage obtained using equations (1) and (3), blue line. It can be seen in figure 5 that the total output voltage of the guitar is significantly higher than the body-borne voltage across virtually the entire frequency range covered (10Hz to 12800Hz). The only significant exception to this is a peak in the body-borne voltage contribution at approximately 700Hz where the body-borne contribution reaches a similar level to the total voltage output, although it never exceeds it. In general, for the low E-string, the body borne contribution was between 30 and 50dB lower than the total voltage output across virtually the whole of the frequency range shown. This implies that the tone of this specific guitar is not affected by the body-borne vibrations at least for the low E-string shown here. Results for other strings gave similar results.

As mentioned in the previous section this result only shows the extent to which the body vibration affects the output voltage of the guitar. Another mechanism by which the guitar body could affect the tone or sustain of a solid body of an electric guitar is though the impedance terminations of the strings at the bridge and nut and the impact this has on the string motion; this can affect the vibrations of the string at different frequencies by different amounts. This is a subject for further research. It can be concluded however that the body borne vibrations for this specific guitar are relatively insignificant in terms of their direct contribution to the guitar's sound and that this contribution is unlikely to be audible. Note that the result shown here is for steady state excitation of the low E-string when excited (steady state) by an E-bow. Further results will be presented at the conference that demonstrate how the body borne contribution to the output voltage compare to the total output voltage for a plucked string as the vibrations decay.

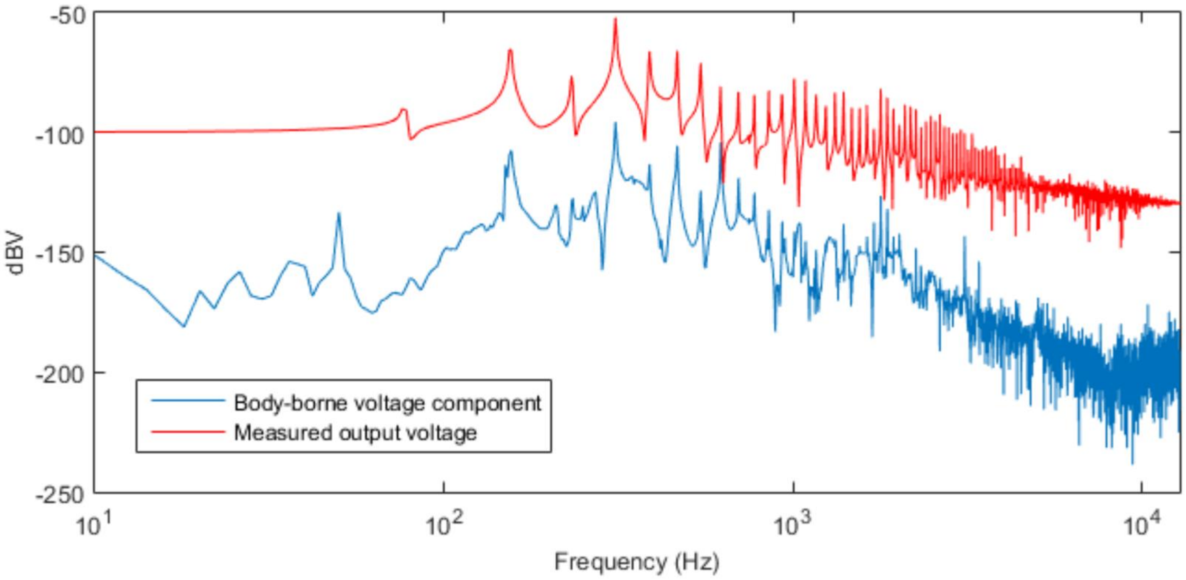

Figure 5 – Comparison of the total measured output voltage of the guitar to the contribution from the guitar body vibration.

Concluding Remarks

A method referred to as 'Vibro-Electric Transfer Path Analysis' has been outlined and demonstrated using a practical example. The approach has been used to determine the body-borne contribution to a solid body electric guitars voltage output so that it may be compared to the total voltage output of the same guitar when the low E-string is excited using an E-bow. For this instrument the contribution to the output voltage was significantly lower than the total output voltage across the entire frequency range tested (10Hz to 12800Hz). In general the body borne contribution was 30 to 50 decibels lower than the total voltage output; body borne vibrations are therefore unlikely to be audible. Further research is required to quantify the extent to which the vibrations of the guitar string are affected by the guitar body and neck as this could also affect the instruments tone and sustain. The results do however imply that the influence of the guitar body material is in this case relatively subtle and that a much greater affect can be had on the tone by modifying the electric signal from the guitar, for example using an EQ. Further results will be presented at the conference including for measurements made on a Gibson Les Paul.

References

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